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UTILIZATION AND ECONOMIC POTENTIAL OF DIFFERENT URANIUMS IN LMFBRs

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ABSTRACT

Under certain conditions, it is more economical to use natural uranium instead of depleted uranium in LMFBRs. The use of natural uranium is restricted to the core region. A critical residence time T_{crit} is determined such that the costs for fuel inventory and consumption are the same in a LMFBR with natural uranium and one using depleted uranium. An optimum residence time T_{opt} is defined such that the cost benefits for using natural instead of depleted uranium are maximized. It was shown that large LMFBRs (>800 MWe) permit T_{crit} values of three years and less. Optimum residence times are of the order of six to seven years. T_{crit} and T_{opt} increase for smaller reactor sizes. Both times depend very strongly on the price for ^{235}U and to a lesser extent on the interest rate. For residence times greater than T_{crit}, savings in inventory and consumption costs of several percent can be expected by replacing depleted uranium by natural uranium.

Utilization and Economic Potential of Different Uraniums in LMFBRs

1. INTRODUCTION

Current LMFBR fuel designs use mixed uranium-plutonium oxide (UO_2-PuO_2) as fuel. The isotopic composition of plutonium is that of LWR discharge plutonium. The uranium used is depleted uranium with an assumed composition of 0.3% ^{235}U and 99.7% ^{238}U. The reason for using depleted uranium rather than natural or enriched uranium is the low cost of this material which is considered negligible compared to the plutonium cost. At a price of \$8/lb U_3O_8 the cost of ^{235}U in natural uranium is of the order of \$3/g. The cost for the conversion of U_3O_8 to UO_2 in the case of natural uranium and UF_6 to UO_2 in the case of depleted uranium are of the same order of magnitude. Table 1 shows these conversion costs for different plant sizes.

In large plant sizes, these costs are less than \$0.50/g ^{235}U. A price of \$10/g is commonly used as price for fissile plutonium (^{239}Pu and ^{241}Pu). This already illustrates that under certain conditions, it might be advantageous to use natural uranium instead of depleted uranium in LMFBRs. But we have to expect that the burnup of ^{235}U as well as the interest rate and the price for U_3O_8 will affect the economics of the utilization of natural vs depleted uranium in LMFBRs.

2. REACTOR MODEL

Two reactor sizes have been chosen: one reactor is in the area of 500 MWt and the other reactor is of the order of 2000 MWt (core plus radial blanket only). Descriptions of these reactors are given in Table 2. Earlier calculations for reactors with natural uranium in the radial blanket indicated that long residence times would be required to justify its use.

TABLE 1. Conversion Cost Estimates

("Reactor Fuel Cycle Costs for Nuclear Power Evaluation," WASH-1099, December 1971)

	Plant Capacity Mt/day	Capital Investment ($\$10^6$)	Annual Operating Cost, ($\$10^6$)
$UF_6 \rightarrow UO_3$	1	2.54	0.615
	10	7.53	1.91
	30	13.4	3.91
$U_3O_8 \rightarrow UO_3$	0.907	2.06	0.425
	9.07	5.36	1.12
	27.2	9.40	2.51
$UO_3 \rightarrow UO_2$	1	1.11	0.364
	10	3.41	1.12

TABLE 2. Reactor Descriptions

MWt	500	2000
Core radius, cm	60	120
Core height, cm	92	92
Radial blanket thickness, cm	20	20
Reflector thickness, cm	10	10
Axial buckling, cm^{-2}	0.00056	0.00056
Core composition		
stainless steel, %	24	24
fuel, %	35	35
sodium, %	41	41
Blanket composition		
stainless steel, %	15	15
fuel, %	50	50
sodium, %	35	35
Reflector		
stainless steel, %	85	85
sodium, %	15	15
Plutonium composition		
Pu-239, %	88	88
Pu-240, %	12	12
Fuel density, smeared (85% T.D.), g/cc	9.35	9.35
Excess reactivity, % $\Delta k/k$	5.0	3.0

Since current designs have upper and lower axial blankets as integral part of the fuel pin, the residence times for axial blankets are the core fuel residence times by definition. Therefore, the use of natural instead of depleted uranium in the axial blanket has not been analyzed and the axial direction was represented by a buckling only.

To avoid unnecessary complications, single-zone cores without control poison were analyzed.

3. CALCULATIONAL APPROACH

The use of natural uranium in LMFBRs instead of depleted uranium can be accommodated in three ways:

(a) natural uranium in the core, depleted uranium in the blanket;

(b) depleted uranium in the core, natural uranium in the blanket;

(c) natural uranium in core and blanket.

To assess the significance of reactor size, a LMFBR with a core and radial blanket power of 500 MWt and one with 2000 MWt were considered. They will be called 500 MWt and 2000 MWt LMFBR.

Table 3 shows the various combinations of natural and depleted uranium which were analyzed. The comparison of the economics of the two fuel types is done by comparing the cost of fuel inventory and consumption (a production). The use of natural uranium instead of depleted uranium leads to a reduction of plutonium inventory and consumption. On the other hand, there are the total costs for natural uranium (principal plus interest) which have to be balanced by savings to justify its use. It is assumed that the natural uranium whenever discharged from the reactor has a zero value. This points already to the burnup as a very important parameter in this assessment. If the burnup of natural uranium is such that only a small fraction

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TABLE 3. List of Cases Which Were Analyzed

Case	Reactor Size, MWt	Uranium Composition	
		Core	Blanket
1	500	D	D
2		N	D
3		D	N
4		N	N
5	2000	D	D
6		N	D
7		D	N
8		N	N

D = natural uranium
N = depleted uranium

of ^{235}U is burned then one cannot expect an improvement in economics. On the other hand, if it were possible to burn all ^{235}U then the economics of utilizing natural uranium were virtually guaranteed. The reference cost for fissile plutonium in oxide form is \$10/gr fissile Pu and for ^{235}U it is \$3.50/gr ^{235}U. The calculations were performed with REBUS[(2)] and DIF1D.[(2)] I did not consider the potential for improving the burnup capability of the fuel by increasing the number of fissions in uranium as observed in irradiation experiments[3] since this effect cannot be described quantitatively at the present time.

4. ECONOMICS EQUATIONS AND CRITICAL RESIDENCE TIME

In the following, the various cost components will be discussed which are of importance for the assessment of natural vs depleted uranium in LMFBRs.

We assume that the plutonium inventory I changes linearly with time. With δI... annual change in plutonium inventory in kg, T... cycle time in calendar years, I_o... initial plutonium inventory in kg, we obtain

$$I(T) \;=\; I_o - T\delta I \quad . \tag{1}$$

Neglecting out-of-pile inventories, the average plutonium inventory $\overline{I}$ can then be written as

$$\overline{I} \;=\; I_o - \tfrac{1}{2}T\delta I \quad . \tag{2}$$

The change in plutonium inventory G over T years is

$$G \;=\; T\delta I \quad . \tag{3}$$

Since the uranium discharged from the reactor will not be used again, the average uranium inventory $\overline{F}$ is one-half of the total uranium inventory F_o(kg) or

$$\bar{F} = \tfrac{1}{2} F_0 \quad . \tag{4}$$

The change in uranium inventory H over T calendar years is

$$H = F_0 \quad . \tag{5}$$

The annual cost of inventory and consumption, C, can therefore be expressed as

$$C = (I_0 - \tfrac{1}{2}T\delta I) \cdot iP^{Pu} + \delta I \cdot P^{Pu} + \tfrac{1}{2} F_0 \cdot i \cdot P^U + \frac{F_0 P^U}{T} \quad , \tag{6}$$

with i... annual interest rate, P^{Pu}... \$/kg fissile plutonium, P^U... \$/kg fissile uranium.

With I_0, δI, I_0', $\delta I'$ denoting inventory and inventory changes in a reactor using depleted and natural uranium, respectively, we can write the annual inventory and consumption cost for the LMFBR with depleted uranium, C^D, as

$$C^D = (I_0 - \tfrac{1}{2}T\delta I)\, i \cdot P^{Pu} + \delta I \cdot P^{Pu} \quad , \tag{7}$$

and for the LMFBR with natural uranium, C^N, as

$$C^N = (I_0' - \tfrac{1}{2}T\delta I')\, i \cdot P^{Pu} + \delta I' P^{Pu} + \tfrac{1}{2} F_0 \cdot i\, P^U + \frac{F_0 P^U}{T} \quad . \tag{8}$$

The utilization of natural uranium instead of depleted uranium is justified if

$$C^N \leq C^D \quad . \tag{9}$$

We now introduce a critical residence time T_{crit} such that

$$C^N(T_{crit}) = C^D(T_{crit}) \quad , \tag{10}$$

and determine T_{crit} from Eq. (10).

With

$$p = \frac{i(I_0 - I_0' - \tfrac{1}{2}F_0R) + (\delta I - \delta I')}{\tfrac{1}{2}i(\delta I' - \delta I)} \tag{11}$$

$$q = \frac{2F_0R}{i(\delta I - \delta I')} \tag{12}$$

$$R = \frac{P^U}{P^{Pu}} \tag{13}$$

we obtain

$$T_{crit} = -\frac{p}{2} - \sqrt{\frac{p^2}{4} - q} > 0 \tag{14}$$

as the shortest residence time necessary to balance the cost for the utilization of natural vs. depleted uranium.

Because C^D is a linear function of T and C^N is a linear function of T plus a $\frac{1}{T}$ term, Eq. (1) has two solutions (see Fig. 1). The second solution T_2 has not been discussed since $T_2 > T_{crit}$. It means, however, that for very long residence times the system with depleted uranium will be favored again. The reason for this behavior is the fact that the plutonium inventory changes decrease linearly with time whereas the change for the uranium consumption is proportional to $\frac{1}{T}$.

Because of the structure of C^N and C^D we can define an optimum time T_{opt} which assures the greatest savings in inventory and consumption cost whenever depleted uranium is replaced by natural uranium. It is obtained from

$$\frac{d(C^N - C^D)}{dT} = 0 \tag{15}$$

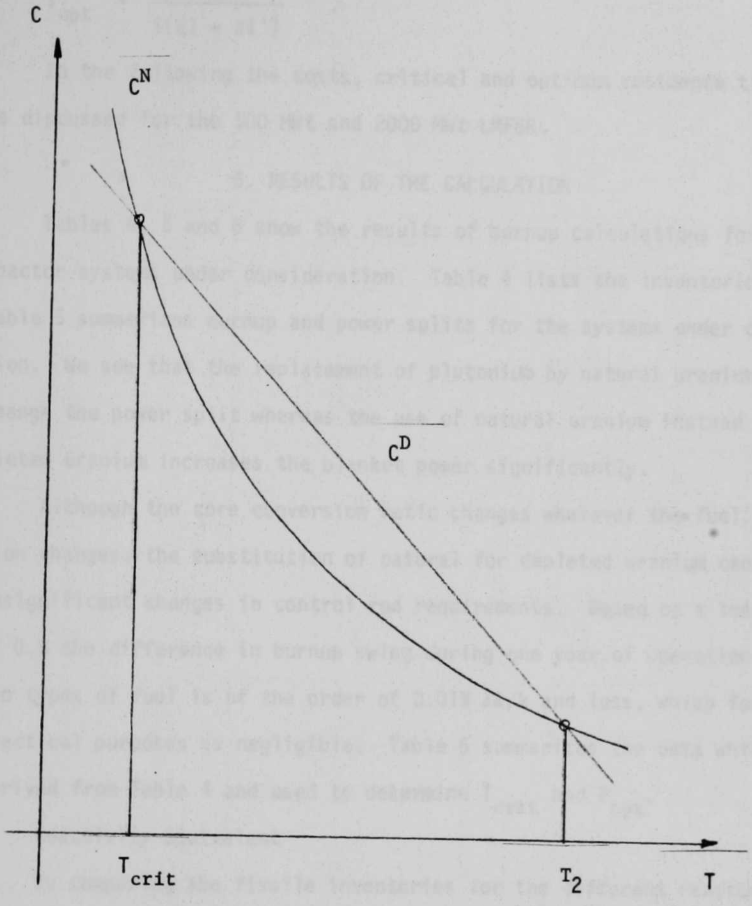

Figure 1. Schematic Representation of C^N and C^D

as

$$T_{opt} = \frac{2F_oR}{i(\delta I - \delta I')} \quad . \tag{16}$$

In the following the costs, critical and optimum residence times will be discussed for the 500 MWt and 2000 MWt LMFBR.

5. RESULTS OF THE CALCULATION

Tables 4, 5 and 6 show the results of burnup calculations for the two reactor systems under consideration. Table 4 lists the inventories and Table 5 summarizes burnup and power splits for the systems under consideration. We see that the replacement of plutonium by natural uranium does not change the power split whereas the use of natural uranium instead of depleted uranium increases the blanket power significantly.

Although the core conversion ratio changes whenever the fuel composition changes, the substitution of natural for depleted uranium causes only insignificant changes in control rod requirements. Based on a load factor of 0.8 the difference in burnup swing during one year of operation for the two types of fuel is of the order of 0.01% $\Delta k/k$ and less, which for most practical purposes is negligible. Table 6 summarizes the data which were derived from Table 4 and used to determine T_{crit} and T_{opt}.

A. Reactivity Equivalent

By comparing the fissile inventories for the different reactor configurations we can determine the ^{235}U reactivity worth equivalent to fissile plutonium. Table 7 shows these equivalents for the two reactor sizes.

About 1.2 kg ^{235}U has to be added to the core for each kg of core ^{239}Pu removed from the core to maintain the same criticality. If one tries to compensate for one kg of core ^{239}Pu by enriching the uranium in the blanket then 13.4 kg and 31 kg of ^{235}U are needed for the 500 MWt and 2000 MWt LMFBR respectively.

$$T_{opt} = \frac{2F_c R}{\{(I1 - \lambda I')\}} \qquad (16)$$

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TABLE 4. 500 MWt LMFBR Inventories

Case	1		2		3		4	
Irradiation Time, full power days	0	500	0	500	0	500	0	500
Core Inventory, kg								
U-235	7.1	3.9	16.7	9.3	7.1	4.0	16.7	9.3
U-238	2363.1	2178.4	2361.8	2177.9	2364.3	2180.8	2363.0	2180.2
Pu-239	557.5	455.8	550.2	451.6	556.5	455.9	549.1	451.6
Pu-240	75.6	105.7	74.6	104.3	75.4	105.4	74.4	103.9
Pu-241	0	6.5	0	6.3	0	6.4	0	6.3
Pu-242	0	0.3	0	0.3	0	0.3	0	0.3
total fissile Pu	557.5	462.3	550.2	457.9	556.5	462.3	549.1	457.9
Blanket Inventory, kg								
U-235	10.0	8.2	10.0	8.1	23.4	19.0	23.4	19.0
U-238	3326.9	3239.1	3326.9	3239.4	3313.3	3226.1	3313.3	3226.4
Pu-239	0	74.9	0	74.7	0	74.2	0	74.0
Pu-240	0	1.54	0	1.5	0	1.5	0	1.5
Pu-241	0	0.0	0	0.0	0	0.0	0	0.0
Pu-242	0	0.0	0	0.0	0	0.0	0	0.0
total fissile Pu	0	74.9	0	74.7	0	74.2	0	74.0
Total Fissile Pu Inventory, kg	557.5	537.2	550.2	532.6	556.5	536.6	549.1	531.9

TABLE 4 (cont'd) 2000 MWt LMFBR Inventories

Case	5		6		7		8	
Irradiation Time, full power days	0	500	0	500	0	500	0	500
Core Inventory, kg								
U-235	30.1	14.4	70.7	33.9	30.1	14.4	70.7	34.0
U-238	10021.2	9033.5	10017.6	9033.8	10022.0	9037.5	10018.6	9037.4
Pu-239	1727.8	1525.4	1694.6	1508.1	1727.0	1525.6	1693.8	1508.3
Pu-240	234.2	368.1	229.7	361.3	234.1	367.7	229.6	360.9
Pu-241	0	26.5	0	25.9	0	26.5	0	25.8
Pu-242	0	1.9	0	1.9	0	1.9	0	1.9
total fissile Pu	1727.8	1551.9	1694.6	1534.0	1727.0	1522.0	1693.8	1534.1
Blanket Inventory, kg								
U-235	18.6	15.4	18.6	15.5	43.4	36.1	43.4	36.1
U-238	6178.5	6034.6	6178.5	6034.8	6153.3	6009.4	6153.3	6009.7
Pu-239	0	125.2	0	125.0	0	124.9	0	124.7
Pu-240	0	2.4	0	2.3	0	2.3	0	2.3
Pu-241	0	0.0	0	0.0	0	0.0	0	0.0
Pu-242	0	0.0	0	0.0	0	0.0	0	0.0
total fissile Pu	0	125.2	0	125.0	0	124.9	0	124.7
Total Fissile Pu Inventory, kg	1727.8	1677.1	1694.6	1659.0	1727.0	1676.9	1693.8	1658.8

TABLE 5. Burnup, Annual Burnup Swing and Power Split Summary

Time, fpd	Power Fraction				Burnup, MWd/t		U^{235} Enrichment				U^{235} Burnup, %		Annual Burnup Swing, % Δk/k
	T = 0		T = 500		T = 500		T = 0		T = 500				
Case	Core	Blanket	Core	Blanket	Core	Blanket	Core	Blanket	Core	Blanket	Core	Blanket	
1	97.7%	2.3%	92.4%	7.6%	79,143	3,687	0.3%	0.3%	0.181%	0.25%	39.7%	16.7%	7.28
2	97.7%	2.3%	92.5%	7.5%	79,160	3,674	0.7%	0.3%	0.424%	0.25%	39.4%	16.7%	7.30
3	96.9%	3.1%	91.7%	8.3%	78,517	4,250	0.3%	0.7%	0.181%	0.597%	39.7%	14.7%	7.20
4	96.9%	3.1%	91.8%	8.2%	78,535	4,237	0.7%	0.7%	0.424	0.597%	39.4%	14.7%	7.22
5	99.17%	0.83%	97.11%	2.89%	81,725	2,938	0.3%	0.3%	0.159%	0.255%	47.0%	15.0%	5.35
6	99.17%	0.83%	97.11%	2.89%	81,731	2,933	0.7%	0.3%	0.374%	0.255%	46.6%	15.0%	5.41
7	98.86%	1.14%	96.76%	3.24%	81,446	3,480	0.3%	0.7%	0.159%	0.597%	47.0%	14.7%	5.31
8	98.86%	1.14%	96.76%	3.24%	81,452	3,474	0.7%	0.7%	0.374%	0.597%	46.6%	14.7%	5.37

TABLE 5. Burnup, Annual Burnup Swing and Power Split Summary

Time, fpd	Power Fraction				Burnup, MWd/t		U^{235} Enrichment				U^{235} Burnup, %		Annual Burnup Swing, % $\delta k/k$
	T = 0		T = 500		T = 500		T = 0		T = 500				
Case	Core	Blanket	Core	Blanket	Core	Blanket	Core	Blanket	Core	Blanket	Core	Blanket	
1	97.7%	2.3%	92.4%	7.6%	79,143	3,687	0.3%	0.3%	0.181%	0.255%	39.7%	16.7%	7.28
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TABLE 6. Summary of Input Data for Eqs. (7), (8), (14) and (16)

Case	I_o, kg	I_o-I(500), kg	δI,* kg	F_o, kg
1	557.5	20.3	11.86	--
2	550.2	17.6	10.28	16.7
3	556.5	19.9	11.62	23.4
4	549.1	17.2	10.04	40.1
5	1727.8	50.7	29.61	--
6	1694.6	35.6	20.79	70.7
7	1727.0	50.1	29.26	43.4
8	1693.8	35.0	20.44	114.1

*Based on a load factor of 0.8.

TABLE 7. U^{235} Reactivity Worth Equivalents for 1 kg Pu^{239} in the Core

Size	Core	Radial Blanket
500 MWt	1.18 kg	13.4 kg
2000 MWt	1.22 kg	31 kg

B. Critical Residence Times

In the following, critical residence times will be discussed for the two LMFBRs as well as optimum residence times and potential fuel cycle cost savings. The discussion of these savings will be restricted to a discussion of fissile inventory and consumption charges.

Although burnup calculations were performed for all eight configurations, another restriction was introduced as a result of these calculations. Inserting the results from Table 6 into Eqs. (11) and (12) we see that $q > 0$ in all cases but $p < 0$ is fulfilled only for cases 2 and 6 (i.e., the exchanges of depleted uranium for natural uranium in the core). In all the other cases we obtain $p > 0$ whichmeans $T_{crit} < 0$. The discussion of critical residence times and optimum residence times is therefore restricted to the cases where the depleted uranium in the core is replaced by natural uranium.

1) Reference conditions

The base case is characterized by the following assumptions

a. $P^{Pu} = \$10^4$

b. $P^U = \$3.5 \cdot 10^3$

c. $i = 0.15$

d. load factor = 0.8

Unless stated otherwise, these assumptions are used throughout the calculation.

2) C^D and C^N as a function of residence time

Both C^D and C^N decrease as the residence time increases. C^D decreases since the average fissile inventory decreases with increasing residence time. C^N decreases for the same reason, but in addition the consumption charge for ^{235}U decreases with $\frac{1}{T}$. As shown in Tables 8 and 9 and Figs. 2 and 3, C^D decreases linearly with time whereas C^N decreases very fast for small values

TABLE 8. Fuel Inventory Plus Consumption Costs for the 500 MW LMFBR

T, yrs.	$C^D(\$10^5)$	$C^N(\$10^5)$	$C^D - C^N(\$10^5)$	$\frac{C^D - C^N}{C^D} \cdot 100\%$
1	9.46	9.83	-0.37	-3.9
1.5	9.42	9.60	-0.18	-1.9
2	9.37	9.46	-0.09	-1.0
2.5	9.33	9.37	-0.04	-0.4
3	9.28	9.29	-0.01	-0.1
3.5	9.24	9.22	0.02	0.2
4	9.19	9.16	0.03	0.3

TABLE 9. Fuel Inventory Plus Consumption Costs for the 2000 MWt LMFBR

T, yrs.	$C^D(\$10^6)$	$C^N(\$10^6)$	$C^D - C^N(\$10^6)$	$\frac{C^D - C^N}{C^D} \cdot 100\%$
1	2.87	3.00	-0.13	-4.5
1.5	2.85	2.91	-0.06	-2.1
2	2.84	2.86	-0.02	-0.7
2.5	2.83	2.83	0	0
3	2.82	2.81	0.01	0.4
3.5	2.81	2.79	0.02	0.7
4	2.80	2.77	0.03	1.1

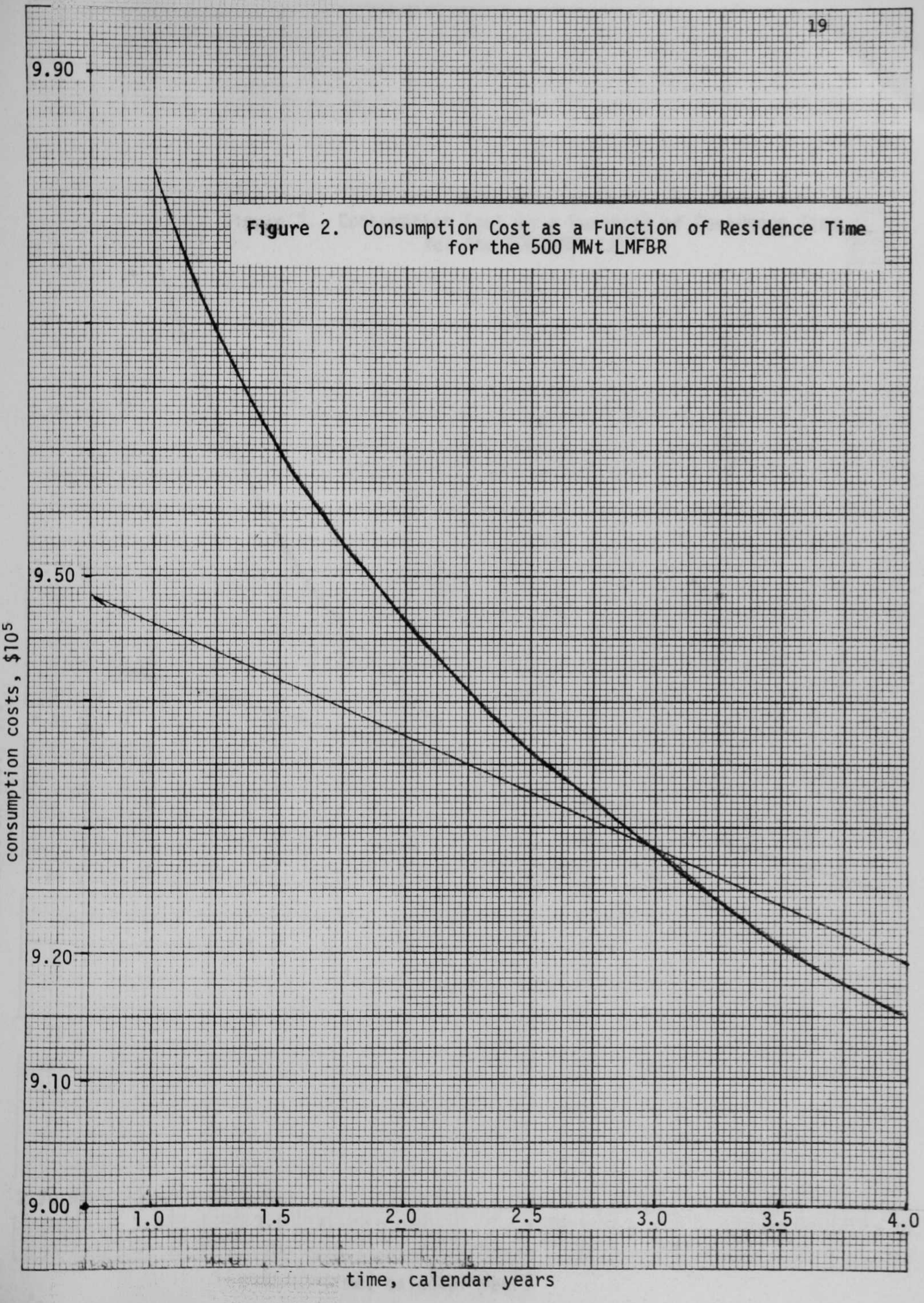


Figure 2. Consumption Cost as a Function of Residence Time for the 500 MWt LMFBR

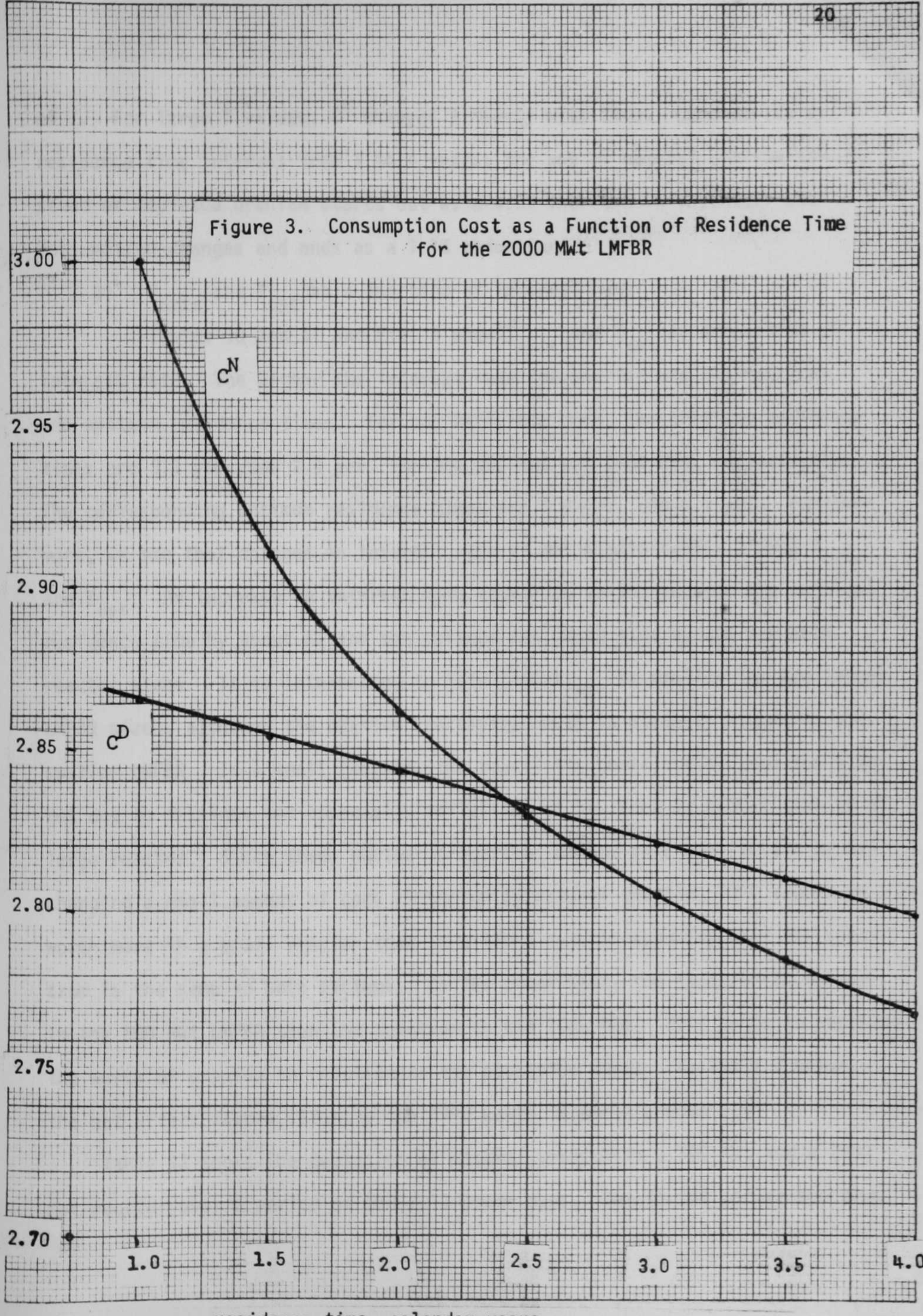


Figure 3. Consumption Cost as a Function of Residence Time for the 2000 MWt LMFBR

of T. For large T values, C^N changes linearly with time. Considering a residence time interval from 1 to 4 years, the use of natural uranium instead of depleted uranium starts out as a 4.5% increase in inventory and consumption changes and ends as a 1.1% reduction.

3) T_{crit} and T_{opt} as a function of interest rate

Tables 10 and 11 and Fig. 4 show T_{crit} and T_{opt} as a function of interest rate. The higher the interest rate the shorter are the critical and optimum residence times. For our reference case, the critical residence times are 3.1 yrs. and 2.4 yrs. for the 500 MWt and 2000 MWt, respectively. The corresponding optimum residence times are 7.0 yrs. and 6.1 yrs. Furthermore, we see that changes in interest rate do not significantly affect T_{crit} and T_{opt}. An increase in interest rate from 7.5% to 15% reduces the critical residence time by about 8% and the optimum residence time by 29% for both reactor sizes. It is interesting to note that T_{crit} is smaller for the larger LMFBR sizes, although the uranium reactivity worth is slightly higher in the smaller LMFBR. In a small reactor, the reactivity contribution from the blanket due to fissions and especially reflection of neutrons is higher than in a large reactor. Since these nuclear properties change only very little by exchanging a small amount of core plutonium by natural uranium, ^{235}U should be worth more in a small reactor than in a large reactor assuming that the spectrum is the same in both systems. On the other hand, the spectrum is harder in the 500 MWt LMFBR than the spectrum in the 2000 MWt. This tends to decrease the worth of uranium in relation to the plutonium worth. As Table 7 shows, the net effect favors slightly the ^{235}U worth in small LMFBRs.

Table 12 shows the depletion of natural uranium in a 500 MWt and a 2000 MWt reactor over a period of 500 full power days. Due to the softer spectrum of T. For large T values, C^{N} changes linearly with time. Considering a residence time interval from 1 to 4 years, the use of natural uranium instead of depleted uranium starts out as a 4.5% increase in inventory and consumption changes and ends as a 1.1% reduction.

3) T_{crit} and T_{opt} as a function of interest rate

Tables 10 and 11 and Fig. 4 show T_{crit} and T_{opt} as a function of interest rate. The higher the interest rate the shorter are the critical and optimum residence times. For our reference case, the critical residence times are 3.1 yrs. and 2.4 yrs. for the 500 MWt and 2000 MWt, respectively. The corresponding optimum residence times are 7.0 yrs. and 5.7 yrs. Furthermore, we see that changes in interest rate do not significantly affect T_{crit} and T_{opt}. An increase in interest rate from 7.5% to 15% reduces the critical residence time by about 8% and the optimum residence time by 25% for both reactor sizes. It is interesting to note that T_{crit} is smaller for the larger LMFBR sizes, although the uranium reactivity worth is slightly higher in the smaller LMFBR. In a small reactor, the reactivity contribution from the blanket due to fissions and especially reflection of neutrons is higher than in a large reactor. Since these nuclear properties change only very little by exchanging a small amount of core plutonium by natural uranium, ^{238}U should be worth more in a small reactor than in a large reactor assuming that the spectrum is the same in both systems. On the other hand, the spectrum is harder in the 500 MWt LMFBR than the spectrum in the 2000 MWt. This tends to decrease the worth of uranium in relation to the plutonium worth. As Table 7 shows, the net effect favors slightly the ^{238}U worth in small LMFBRs.

Table 12 shows the depletion of natural uranium in a 500 MWt and a 2000 MWt reactor over a period of 500 full power days. Due to the softer spectrum

TABLE 10. Critical Residence Time T_{crit} and Optimum Residence Time, T_{opt}, as a Function of Interest Rate for the 500 MWt LMFBR

Interest Rate i	T_{crit}, yr.	T_{opt}, yr.
0	3.70	
0.01	3.67	27.2
0.02	3.63	19.2
0.05	3.52	12.2
0.075	3.43	9.93
0.10	3.33	8.60
0.125	3.23	7.69
0.15	3.14	7.02
0.20	2.94	6.08
0.25	2.74	5.44
0.30	2.55	4.97

TABLE 11. Critical Residence Time T_{crit} and Optimum Residence Time, T_{opt}, as a Function of Interest Rate for the 2000 MWt LMFBR

Interest Rate i	T_{crit}, yr.	T_{opt}, yr.
0	2.83	
0.01	2.80	23.8
0.02	2.78	16.8
0.05	2.69	10.6
0.075	2.62	8.69
0.10	2.55	7.52
0.125	2.48	6.73
0.15	2.41	6.14
0.20	2.27	5.32
0.25	2.14	4.76
0.30	2.01	4.34

Figure 4. Critical Residence Time as a Function of Interest Rate for 500 MWt and 2000 MWt LMFBRs

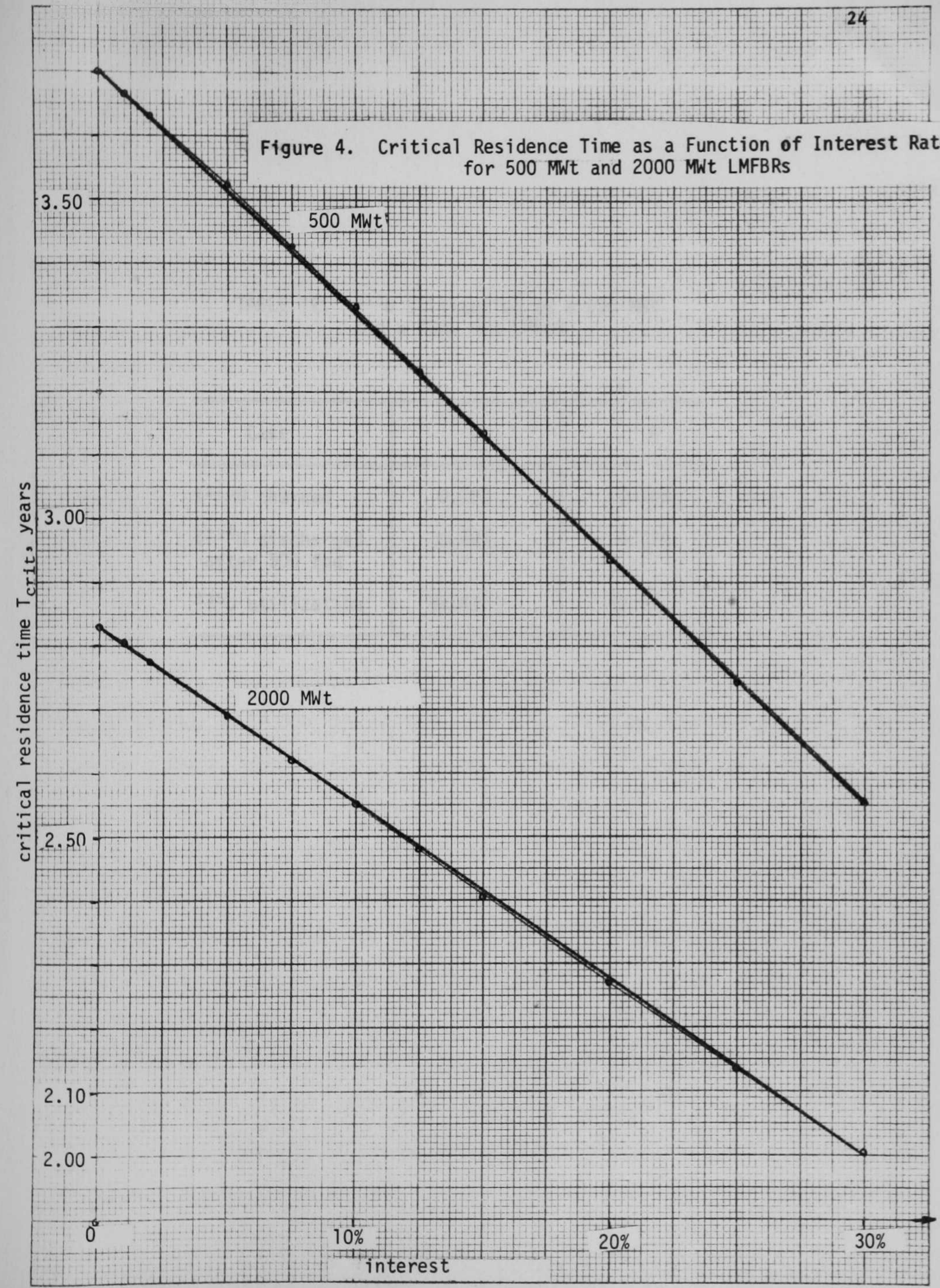


Figure 4. Critical Residence Time as a Function of Interest Rate for 500 MWt and 2000 MWt LMFBRs

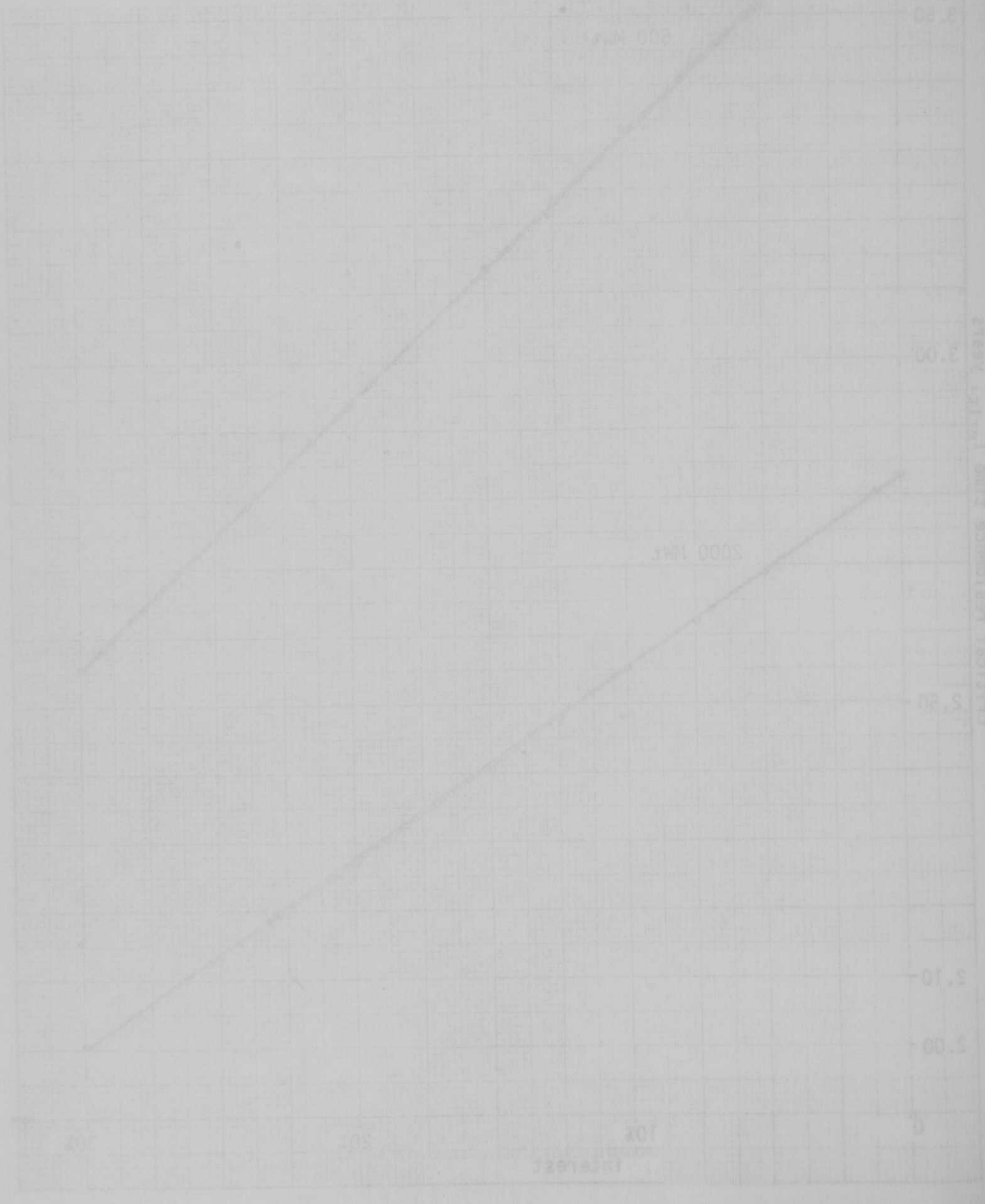


TABLE 12. ^{235}U Utilization in a 500 MWt and a 2000 MWt LMFBR

Case	2	6
%^{235}U charged	0.700	0.700
%^{235}U discharged after 500 fpd	0.424	0.374
^{235}U utilization	39.4%	46.6%

and the smaller leakage, significantly more ^{235}U is burned in the large LMFBR than in the small LMFBR. This explains why the critical residence time in the 2000 MWt is about 30% shorter than in the 500 MWt reactor.

4) T_{crit} and T_{opt} as a function of the ^{235}U price

Tables 13 and 14 and Fig. 5 show critical and optimum residence time as a function of the ^{235}U price. While the effect of changes in the interest rate has only little effect on T_{crit} and T_{opt}, the ^{235}U price is the key parameter in assessing the utilization of depleted vs. natural uranium. Increasing the ^{235}U price from \$3.50/gr ^{235}U to \$4.0/gr ^{235}U increases the critical residence time by more than 20% and the optimum residence time by 7% for both reactor sizes.

6. CONCLUSIONS

Under certain conditions, it is more economical to use natural uranium instead of depleted uranium in the LMFBR. A critical residence time T_{crit} can be defined such that the costs for inventory and consumption are the same in a LMFBR with natural uranium and one using depleted uranium. The use of natural uranium is restricted to the core region. In a small reactor system (500 MWt for core and radial blanket which corresponds to a total reactor output of approximately 200-250 MWe) the residence time for the fuel has to be at least three years to justify the utilization of natural uranium instead of depleted uranium on economical grounds. The larger LMFBR (i.e., 2000 MWt which is equivalent to approximately 800 MWe) permits critical residence times of less than 3 years for fuel assemblies containing natural uranium in order to stay under the inventory and consumption cost of a LMFBR using depleted uranium. Shorter critical residence times must be expected if natural uranium is being used for fuel assemblies in the center core region and the smaller leakage, significantly more ^{238}U is burned in the large LMFBR than in the small LMFBR. This explains why the critical residence time in the 2000 MWt is about 30% shorter than in the 500 MWt reactor.

4) T_{crit} and T_{opt} as a function of the ^{235}U price

Tables 13 and 14 and Fig. 6 show critical and optimum residence time as a function of the ^{235}U price. While the effect of changes in the interest rate has only little effect on T_{crit} and T_{opt}, the ^{235}U price is the key parameter in assessing the utilization of depleted vs. natural uranium. Increasing the ^{235}U price from $3.50/gr ^{235}U to $4.0/gr ^{235}U increases the critical residence time by more than 20% and the optimum residence time by 7% for both reactor sizes.

6. CONCLUSIONS

Under certain conditions, it is more economical to use natural uranium instead of depleted uranium in the LMFBR. A critical residence time T_{crit} can be defined such that the costs for inventory and consumption are the same in a LMFBR with natural uranium and one using depleted uranium. The use of natural uranium is restricted to the core region. In a small reactor system (500 MWt for core and radial blanket which corresponds to a total reactor output of approximately 200-250 MWe) the residence time for the fuel has to be at least three years to justify the utilization of natural uranium instead of depleted uranium on economical grounds. The larger LMFBR (i.e., 2000 MWt which is equivalent to approximately 800 MWe) permits critical residence times of less than 3 years for fuel assemblies containing natural uranium in order to stay under the inventory and consumption cost of a LMFBR using depleted uranium. Shorter critical residence times must be expected if natural uranium is being used for fuel assemblies in the center core region

TABLE 13. Critical Residence Time T_{crit} and Optimum Residence Time T_{opt} as a Function of ^{235}U Price for the 500 MWt LMFBR

U^{235} Price $/gr. U^{235}	T_{crit}, yr.	T_{opt}, yr.
3.00	2.50	6.50
3.25	2.80	6.77
3.50	3.14	7.02
3.75	3.50	7.27
4.00	3.90	7.51
4.50	4.91	7.96
5.00	6.58	8.39

TABLE 14. Critical Residence Time T_{crit} and Optimum Residence Time T_{opt} as a Function of ^{235}U Price for the 2000 MWt LMFBR

U^{235} Price $/gr. U^{235}	T_{crit}, yr	T_{opt}, yr
3.00	1.96	5.69
3.25	2.18	5.92
3.50	2.41	6.14
3.75	2.66	6.36
4.00	2.92	6.57
4.5	3.53	6.96
5.00	4.28	7.34

Figure 5. Critical Residence Time as a Function of U^{235} Price for the 500 MWt and 2000 MWt LMFBRs

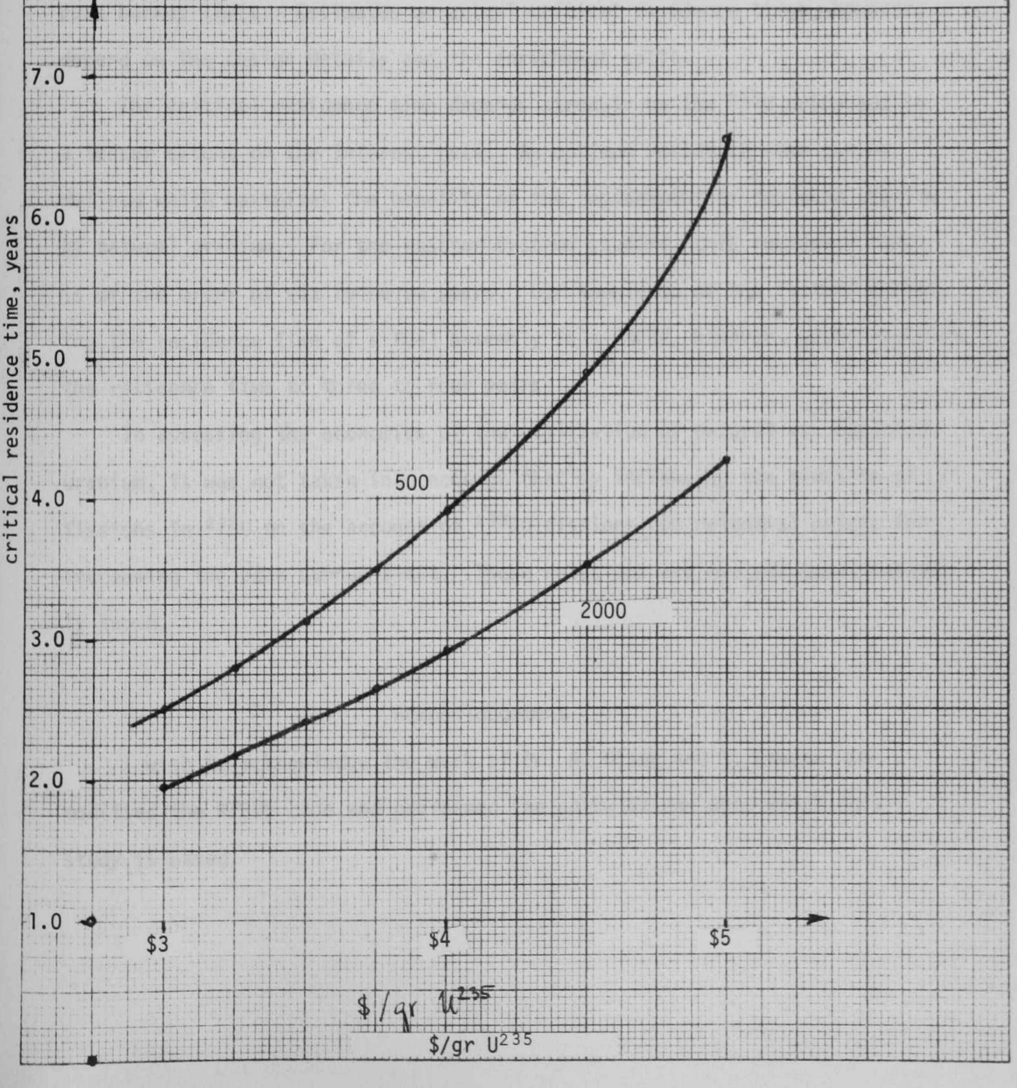
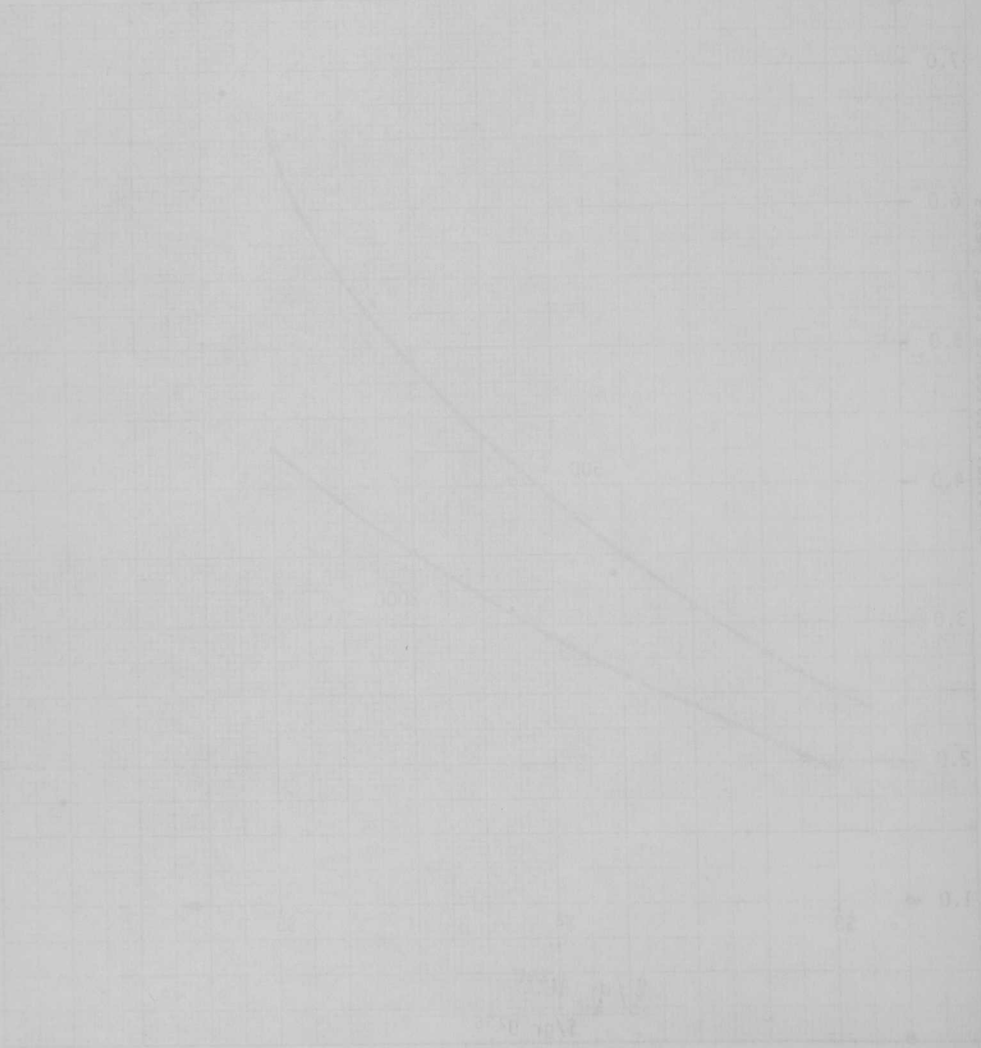


Figure 5. Critical Residence Time as a Function of UF6 Price for the 500 MWt and 2000 MWt LMFBRs



only (see Fig. 6), since the utilization of ^{235}U is more than 70% at the core center and below 30% at the core periphery for a 500 full power day period. The utilization of ^{235}U in assemblies close to the core-blanket interface can be improved by increasing the residence time for those assemblies, however, the limiting time for those assemblies is usually not the peak burnup limit. Estimates on actual critical residence times, however, depend on the design details and the enrichment split.

The critical residence time depends strongly on the ^{235}U price and to a lesser extent on the interest rate. An optimum residence time can be defined which maximizes the benefits of the replacement of depleted uranium by natural uranium. For the reactor systems studied, this residence time is of the order of six to seven years. Our knowledge of the factors affecting the residence time of a fuel assembly in a LMFBR, however, would restrict the residence time to three to four years.

In assessing the economics of the utilization of natural vs. depleted uranium, it was not taken into account that by increasing the fraction of fissions in ^{235}U on the account of ^{239}Pu fissions the potential exists for increasing the peak burnup limit. These relations are not yet quantitatively known.

Acknowledgement

I wish to acknowledge the work of Dr. A. Olson and I. Lawson who modified the REBUS code and performed the calculations upon which this study is based.

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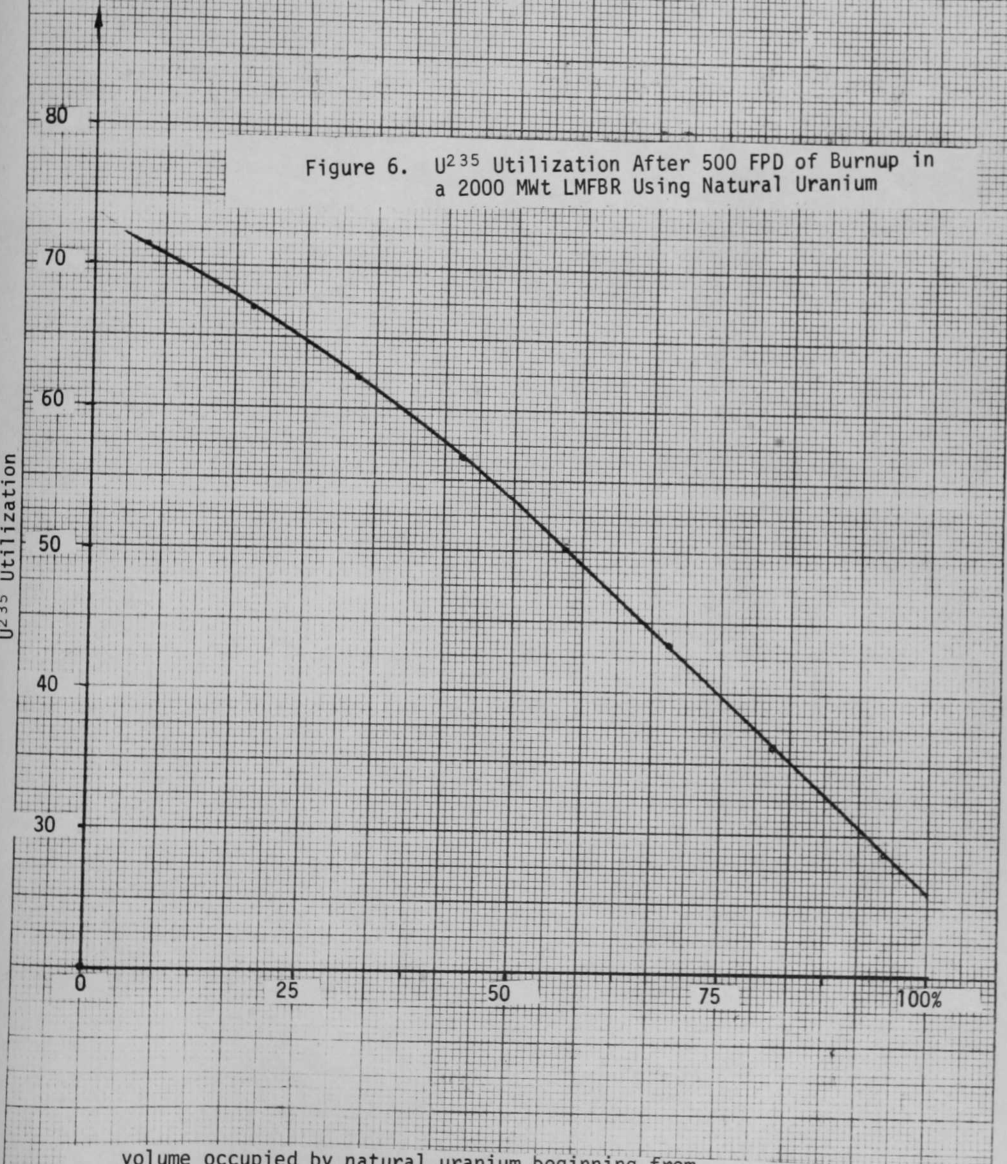

Figure 6. U^{235} Utilization After 500 FPD of Burnup in a 2000 MWt LMFBR Using Natural Uranium

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